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Standard physics is still capable to interpret ∼18 TeV photons from GRB 221009A

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ABSTRACT

It is reported that the Large High Altitude Air Shower Observatory (LHAASO) observed thousands of very-high-energy photons up to ∼18 TeV from GRB 221009A. We study the survival rate of these photons by considering the fact that they are absorbed by the extragalactic background light. By performing a set of 10^6 Monte-Carlo simulations, we explore the parameter space allowed by current observations and find that the probability of predicting that LHAASO observes at least one photons of 18 TeV from GRB 221009A within 2000 seconds is 4–5%. Hence, it is still possible for the standard physics to interpret LHAASO's observation in the energy range of several TeV. Our method can be straightforwardly generalized to study more data sets of LHAASO and other experiments in the future.

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1. INTRODUCTION

More than 5000 photons above 0.5 TeV emitted from GRB 221009A at redshift $z \simeq 0.1505$ were observed by the Large High Altitude Air Shower Observatory (LHAASO) [1] within 2000 seconds after the first detection by Swift, Fermi-GBM, Fermi-LAT, and so on [2]. The highest energetic photons were reported to reach ~ 18 TeV, representing the first observation of photons above 10 TeV from gamma-ray bursts (GRBs). Such observations intrigued studies on photon mixing with axion-like particles Galanti et al. (2022), Lorentz symmetry violation Li & Ma (2022), and both Baktash et al. (2022). In our work, we will investigate the survival probability of multi-TeV photons from GRB 221009A by considering the fact that they are significantly absorbed by the extragalactic background light intervening between the GRB and the Earth. We will further show whether the standard physics is still capable to interpret current observations.

Very-high-energy photons can dissipate their energies via annihilation with photons in cosmic microwave background (CMB) and extragalactic background light (EBL), producing electron-positron pairs. The threshold of this channel to happen is $E_{\rm th} = m_e^2/E_{\rm b}$, where m_e and E_b are the mass of electrons and the averaged energy of background light, respectively. Therefore, for CMB photons, this threshold is hundreds of TeV, implying that we can safely disregard the effect of CMB photons. However, the energy of EBL photons can be higher by several orders of magnitude than the CMB photons, changing the threshold to be lower by the same magnitude. For example, the threshold is ~ 2.6 TeV if we consider $E_b \sim 0.1$eV. Therefore, we should take into account the suppression effect of EBL photons on the detected flux of ~ 18 TeV photons by LHAASO.

2. FLUX OF TEV PHOTONS AND EBL ATTENUATION

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[1] https://gcn.gsfc.nasa.gov/gcn3/32677.gcn3
[2] https://gcn.gsfc.nasa.gov/gcn3_archive.html

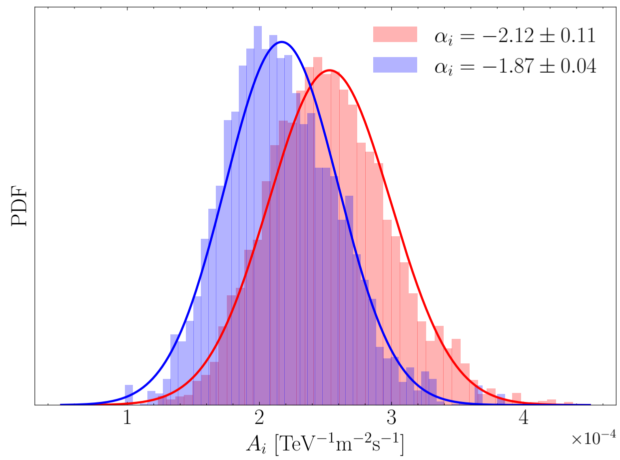

Figure 1. Posterior probability distribution functions of A_i estimated in the case of priors $\alpha_i = -1.87 \pm 0.04$ (blue) and -2.12 ± 0.11 (red), respectively.

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The EBL-suppressed flux F_o depends on the intrinsic flux F_i and the optical depth $e^{-\tau}$ due to absorption by EBL. Therefore, we have

$$F_o(E) = F_i(E) e^{-\tau(E,z)} \ , \tag{1}$$

where E is the observed energy of photons and z is the redshift of GRB 221009A. We use the tabulated data of the EBL and optical depth measured by Ref. Domínguez et al. (2011). The intrinsic flux of photons is approximated to be a power-law MAGIC Collaboration et al. (2019)

$$F_i(E) = A_i \left(\frac{E}{0.5\mathrm{TeV}} \right)^{\alpha_\mathrm{i}} \ , \tag{2}$$

where A_i and α_i, respectively, stand for the intrinsic flux and spectral index at the pivot energy scale 0.5 TeV. Considering the reports of Fermi-LAT, we have two measured values of α_i, namely, -1.87 ± 0.04 [3] and -2.12 ± 0.11 [4], which were obtained at 0.1–1 GeV, but in different temporal intervals. We leave A_i to be determined by LHAASO as follows.

By considering the performance of LHAASO Cao et al. (2019), we predict the number of events with energy above 0.5TeV to be

$$N_{>0.5\mathrm{TeV}} = T \int_{0.5\mathrm{TeV}} F_o(E) S_\mathrm{eff}(E, \theta) dE \ , \tag{3}$$

where S_eff is the effective area of LHAASO-WCDA, as provided in Fig. 6 of Chapter 3 in Ref. Cao et al. (2019), $\theta \simeq 28^\circ$ is the zenith angle of GRB 221009A, and $T = 2000$ seconds is the duration of LHAASO observation.

To explore the parameter space, we perform Bayesian analysis by considering the fact that the number of photons above 0.5TeV is more than 5000, as reported by LHAASO [5]. We assume that the event number follows Poisson distribution with probability distribution function (PDF), i.e.

$$p(k) = \lambda^k e^{-\lambda} / k! \tag{4}$$

with $\lambda = 5000$ being the expectation and $k = N_{>0.5\mathrm{TeV}}$. Our results and conclusion are remained when choosing other value of λ within $[5000, 6000)$. We implement the Bayesian inference by using the affine-invariant Markov chain Monte Carlo (MCMC) ensemble sampler in *emcee* Foreman-Mackey et al. (2013). We assume that A_i has a uniform prior in the range $[1 \times 10^{-4}, 7 \times 10^{-4}]$ in units of TeV^{-1}m^{-2}s^{-1}. We take the aforementioned Fermi-LAT measurements of the

[3] https://gcn.gsfc.nasa.gov/gcn3/32658.gcn3
[4] https://gcn.gsfc.nasa.gov/gcn3/32637.gcn3
[5] https://gcn.gsfc.nasa.gov/gcn3/32677.gcn3

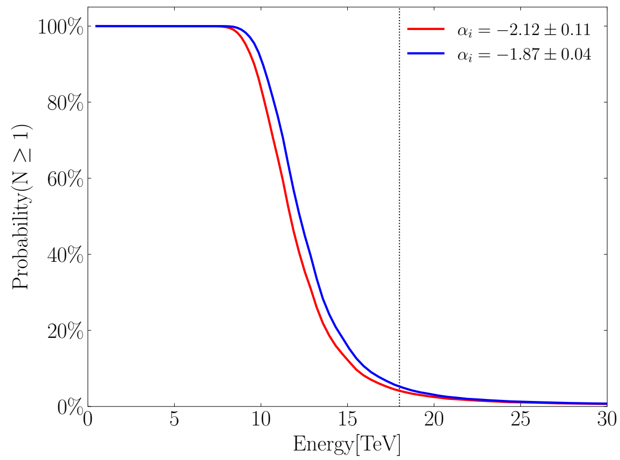

Figure 2. Probability of predicting that LHAASO-WCDA observes at least one photon from GRB 221009A within 2000 seconds. The coloring of curves is consistent with that of Fig. 1.

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spectral index to be Gaussian priors of α_i. The optical depth is sampled by following the tabulated data of median value and uncertainties of τ [6], as described in Ref. Domínguez et al. (2011).

Our results of Bayesian analysis are shown as follows. At 68% confidence level, we find two sets of posteriors of (A_i, α_i), i.e., $A_i = (2.51 \pm 0.46) \times 10^{-4}$ TeV^{-1}m^{-2}s^{-1}, $\alpha_i = -2.13 \pm 0.11$ and $A_i = (2.14 \pm 0.43) \times 10^{-4}$ TeV^{-1}m^{-2}s^{-1}, $\alpha_i = -1.87 \pm 0.04$. We further depict the one-dimensional posterior PDFs of A_i in Fig. 1. In the following, we do simulations via sampling A_i and α_i following their posterior PDFs and τ following the aforementioned tabulated data.

3. PROBABILITY OF DETECTING TEV PHOTONS

Based on the above results, we will estimate the probability of predicting that LHAASO observes at least one photons $\sim$18 TeV from GRB 221009A. During an observation of $T = 2000$ seconds, the event number of photons in the energy range from $(1 - \Delta_E/2)E$ to $(1 + \Delta_E/2)E$ is given by

$$N(E) = T F_o(E) S_{\rm eff}(E, \theta) \Delta_E(E) E \ , \tag{5}$$

where $\Delta_E(E)$ is the energy resolution of LHAASO-WCDA, as provided in Fig. 26 of Chapter 1 in Ref. Cao et al. (2019). We consider the energy range from 0.5 TeV to 30 TeV, with an emphasis on 18 TeV. For each given energy E, we perform a set of 10^6 Monte-Carlo simulations. We count the number of models that predict $N(E) \geq 1$ and compute the corresponding probability via dividing this number by 10^6.

Our results of Monte Carlo simulations are shown in Fig. 2. We find that the probabilities of predicting that LHAASO is capable to detect at least one photons of 18 TeV from GRB 221009A, are about 5.2% and 4.1% in the case of priors $\alpha_i = -1.87 \pm 0.04$ and -2.12 ± 0.11, respectively, respectively. Amongst the above two spectral indices, the former was obtained during 200–800 seconds after trigger, while the latter was obtained during 500–3500 seconds. For comparison, the LHAASO data was accumulated within 2000 seconds after trigger. Based on Ref. Nava (2021), we notice that the flux of photons in the TeV band significantly decreases with time. If the events observed by LHAASO also preserve this property, though such a guess should be tested with the LHAASO data if possible, we expect that the majority of events arrived within the first 1000 seconds. We find that in either case the standard physics is still capable to interpret $\sim$18 TeV photons from GRB 221009A.

4. SUMMARY

In this work, we have investigated the survival rate of very-high-energy gamma rays within the energy range of LHAASO, by taking into account the effect of EBL attenuation. In the framework of standard physics, we simulated

[6] http://side.iaa.es/EBL/

the probability of detecting the $\sim$18 TeV signal from GRB 221009A to be a few percents. Hints of new physics may be displayed at 2.58σ level if photons above 26 TeV from GRB 221009A are observed by LHAASO. The above conclusions might be altered if we consider other measurements of EBL and optical depth, that are beyond the scope of this paper. We would leave such a detailed study to future works. Our research method can be straightforwardly generalized to study more data sets of LHAASO and other experiments in the future.

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